RESEARCH REPORT

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GUGGENHEIM AERONAUTICAL LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

HYPERSONIC RESEARCH PROJECT

Memorandum No. 55

June 1, 1960

USE OF FINE UNHEATED WIRES FOR HEAT TRANSFER MEASUREMENTS IN THE SHOCK TUBE

by

Walter H. Christiansen

ARMY ORDNANCE CONTRACT NO. DA-04-495-Ord-1960

GUGGENHEIM AERONAUTICAL LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California

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page 13 -- Equation (20b) --

now reads $\frac{\dot{Q}_{2D}}{Q_{3D}} \cong 1 + \frac{2}{\lambda} \frac{t}{\tau} + \ldots$

It should read: $\frac{\dot{Q}_{2D}}{Q_{3D}} \cong 1 + \frac{2}{\sqrt{\pi}} \sqrt{\frac{t}{\tau\lambda}}$

page 14 -- last line --

now reads: "a two per cent error in the ...."

It should read: "a ten per cent error in the ...."

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ABSTRACT

This report describes the application of fine cold wires for heat transfer measurements in the shock tube. The use of the calorimetric property of the wire results in a heat transfer instrument with an output of .25 mv/oC and a response lag of less than 1 μsec. The gage construction, calibration, and response characteristics are discussed. Some preliminary results are also presented.

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LIST OF FIGURES

LIST OF SYMBOLS

d	diameter of wire , cm
ℓ, L	length of wire , cm
δ	some characteristic length , cm
ψ	distance measured along wire , cm
α	coefficient of resistivity , $1/{}^{o}C$
ρ	density , $\frac{gm}{cm^3}$
c	specific heat, $\frac{cal}{gm\,{}^{o}C}$
T	temperature , ${}^{o}C$
R	resistance , ohms
σ	specific resistance , ohm cm
AR	aspect ratio , ℓ/d
E	oscilloscope voltage , volts
V	battery voltage, volts
I	current , amps
C	capacitance , farads
U	velocity , cm/sec
k	thermal conductivity $\frac{cal}{{}^{o}C \text{ sec cm}}$
t	time , sec
Q	quantity of heat , cal
q	heat transfer/unit area, $\frac{cal}{cm^2 \text{ sec}}$
m	mass of the wire $\pi \frac{d^2}{4} \ell \rho$, gm
Nu	Nusselt no. $\frac{\dot{Q}}{\pi k \ell \Delta T} = \frac{q d}{k \Delta T}$
τ	time constant $\frac{d^2 \rho c}{4 Nu k}$, sec
s	Laplace transform of time
λ	non-dimensional length $Nu \frac{k_a}{k_w} \left(\frac{\ell}{d}\right)^2$

p. pressure , mm Hg.

Subscripts

$( )_i$ some initial condition

$( )_w$ wire

$( )_r$ recovery temperature of wire

$( )_a$ air

I. INTRODUCTION

A new heat transfer instrument has been developed for use in the shock tube. This report describes in detail the construction, calibration, and use of this instrument. The instrument is a fine "cold wire" that utilizes the transient nature of the hot flows produced in the shock tube for heat transfer or anemometry measurements. Physically, its appearance is similar to an ordinary hot wire anemometer, but conceptually, its application and use is quite different. A photograph of the gage and its mounting is shown in Figure 1. The gage uses only a small excitation current to produce a voltage signal across the wire. There is essentially no joule heating in the wire, and it will practically maintain the temperature of its surroundings before the initiation of the hot flow. After the shock wave passes over the wire, the wire begins to heat up in this flow. This heating continues until the wire reaches an equilibrium temperature or until the hot flow ceases. The wire is assumed to be a perfect calorimeter, that is, all the heat convected to the wire is stored in the wire itself. Calorimetric methods of heat transfer measurements have been used before in the shock tubes. [1,2] The resulting change of wire temperature produces a resistance change of the wire which is conveniently read as a voltage on an oscilloscope.

For quantitative heat transfer measurements, the physical constants α, ρ, c and the geometrical quantities d and ℓ must be known. Thus we have to evaluate two additional physical constants (ρ and c) using this method of heat transfer measurement as compared to ordinary or steady state measurements with hot wires. An electrical calibration method has been developed to evaluate them.

The wires used in this report are made of either tungsten or platinum. The excitation current is adjusted so that there is no appreciable heating of the wire ($\Delta T = T_w - T_i = O(1^{\circ}C)$), resulting in an output signal of .25 mv/oc. Preliminary measurements, calibration technique, end loss corrections, and response characteristics are presented to illustrate the performance of the instrument more fully.

II. CONSTRUCTION OF THE GAGE

The wires can be made of practically any metal such as nickel, aluminum, or platinum. The maximum signal output, tensile strength, and commercial availability should be kept in mind. (See Part III.) In this investigation both platinum and tungsten wires were used with diameters comparable to those of standard hot wires -- roughly .0001" - .001". These are readily available from commercial firms. Either wire gives a good signal due to a flow in the shock tube, but tungsten has the obvious advantage of high tensile strength. However, it is available only in limited sizes.

The wire is conveniently supported by two sewing needles held in a bakelite wedge. (See Figure 1.) The wedge is attached to a side wall plug with electrical leads and inserted into the shock tube. For heat transfer measurements, the wire is placed perpendicular to the flow and centered on the shock tube axis to minimize any shock tube boundary layer and wall effects. The wedge is removable from the plug for convenience in replacing broken wires or wires of different diameters. The electrical connections are made with the pin connectors from Winchester plugs such as type MRE 20S. These are gold plated and make good electrical contact.

The platinum wires are directly soldered to the supports while tungsten must be copper plated first. In the latter case a thin layer of copper is deposited on the whole length of wire using a copper sulphate solution. It is then soldered to the supports. The plating process then is reversed to leave the wire bare. Spot welding the tungsten wire to the supports is another method of attaching it to the needles. Some damage is done to the supports and wire with this method, but it is more convenient and requires less time than copper plating. Both methods result in good electrical connections.

The construction of the gage provides for a fairly large aspect ratio $(\frac{l}{d})$ to minimize any aerodynamic interference of the supports. This aspect ratio is held between 600 and 1200. For constant aspect ratio, the completed gage has a characteristic resistance proportional to the inverse of the diameter.

$$R_w = \frac{\sigma l}{\frac{\pi d^2}{4}} = \frac{4 \sigma AR}{\pi} \left(\frac{1}{d} \right)$$

The gage resistances vary from 2 ohms to 40 ohms at room temperature.

III. METALS FOR USE AS FINE COLD WIRES

The discussion actually falls into three categories: 1) what metals are commercially available for fine wires, 2) what materials are structually superior and 3) what metals will give the largest signal due to heat transfer? The first two questions are not dealt with here, only the latter. The voltage signal is (see Part IV)

$$\dot{E} = I\dot{R}_w = IR_i\alpha_i\dot{T}_w$$

Assuming the wire to be a perfect calorimeter, $\dot{T}w$ can be written in terms of heat transfer $\dot{Q} = \frac{\pi d^2 \ell}{4} \rho c \dot{T}_w$

With $R = \frac{\sigma \ell}{\frac{\pi d^2}{4}}$, we get

$$\dot{E} = \frac{I\dot{Q}}{\left(\frac{\pi d^2}{4}\right)^2}\left(\frac{\sigma\alpha}{\rho c}\right)_w \tag{1}$$

I, Q, and d are fixed by the geometry and flow conditions. Therefore, for maximum $\dot{E}$, $\left(\frac{\sigma\alpha}{\rho c}\right)_w$ must be maximum. The table* below lists some metals in their relative position with respect to this parameter.

Position	Metal	σ	a/oC	g/cm^3	c	$\frac{\sigma\alpha}{\rho c}$
1	Fe	9.8	.0065	7.9	.108	.074
2	Pt	9.8	.0039	21.5	.032	.055
3	Ni	6.9	.006	8.85	.112	.042
4	Pt90Rh10	18.4	.0016	21	.034	.041
5	W	5.5	.0045	19.3	.032	.040
6	Pt90Ir10	22	.001	21.6	.032	.032
7	Aℓ	2.7	.0045	2.7	.226	.02
8	Au	2.4	.0034	19.3	.031	.014

* Physical properties from Ref. (3)

IV. RESPONSE CHARACTERISTICS OF A FINE COLD WIRE

The response time of the instrument is limited by two characteristic times: 1) the characteristic time it takes to set up flow about the wire 2) the characteristic time it takes to heat the wire uniformly throughout its volume.

1) The time required to establish flow over the wire is of order $\frac{5d}{U}$ (assuming 5 body diameters to establish this flow). For the larger wire sizes this time is approximately 1 μsec.

2) Heat diffuses with infinite signal velocity, that is, a pulse source of heat can theoretically be felt everywhere. One can define an effective time for penetration of a pulse of heat as

$$t \sim \frac{\rho c \delta^2}{k}$$

If δ is taken to be equal to one half of the diameter of the wire, then this characteristic time is $t \sim 1.6$ μsec for a 1/2 mil platinum wire and .7 μsec for a tungsten wire. Hence under most conditions in the shock tube, even those that involve small testing times O (10 μsec), the wire can be considered to be in steady flow and uniform in temperature. For smaller wires, of course, the characteristic times would be shorter.

A temperature rise of the wire is accompanied by a resistance variation of the wire. If this variation is moderate (ΔT of the order 200°C), the resistance of the wire is accurately given by

$$R_w = R_i \left(1 + \alpha_i \left(T_w - T_i\right)\right) \tag{2}$$

The subscript i denotes some initial condition where the properties of the wire are known. If a current is passed through the wire, the voltage drop across it is equal to

$$IR_w = E = IR_i \ (1 + \alpha_i \ (T_w - T_i)\ ) \tag{3}$$

The variation in voltage will be ΔE.

$$\Delta E = \Delta I R_w + I \Delta R_w \tag{4}$$

If the voltage source has a high impedance compared to the wire, the current will essentially be constant. This will simplify the computations and reduction of data, although it is not a necessary simplification. Then

$$\Delta E = I \Delta R_w = I R_i \ \alpha_i \ (T_w - T_i) \tag{5}$$

An element made of tungsten with a diameter of .0005" has a resistance of approximately 6 ohms. With $I \doteq 10$ ma. and $\alpha = .004/o$, a voltage of $.24$ mv/o is produced. This seems like a small signal, but it should be remembered that large temperature differences are encountered in the shock tube and the heat content of the wire is small. Therefore the wire may heat up many hundreds of degrees during a run, resulting in a signal of many millivolts.

An ordinary heat balance of the wire is given by*

HEAT STORED =

HEAT PRODUCED INTERIOR + HEAT CONVECTED + HEAT CONDUCTED
(JOULE HEAT) (FORCED CONVECTION) (TO SUPPORTS)

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* At very low densities radiation may have to be taken into account.

With the assumption that the wire does not have any heat conduction losses to the supports and is uniformly heated in any cross-section, there will be no spatial variance of the temperature in the wire. This results in the simple equation

$$\frac{d}{dt} mc\left(T_w - T_i\right) = I^2 R_w + Q_{\substack{\text{FORCED}\\ \text{CONVECTION}}} \tag{6}$$

This equation graphically illustrates the difference between an ordinary hot wire and a cold wire as used in the shock tube. The left hand side of equation 6 is zero for steady state measurements with a hot wire or its use with compensating amplifiers. The Joule heat then equals the forced convection heat transfer. For a cold wire however, the Joule heat term is zero and thus

$$\frac{d}{dt} mc\left(T_w - T_i\right) = Q_{\substack{\text{FORCED}\\ \text{CONVECTION}}} \tag{7}$$

This equation can be readily integrated with the assumption of constant material properties.

$$\int_{T_i}^{T_w} \frac{\frac{\pi d^2 \ell}{4} \rho c \quad dT_w}{q \, \pi d \ell} = \int_0^t dt \tag{.8}$$

$$\frac{d\rho c}{4} \int_{T_i}^{T_w} \frac{dT_w}{q} = t$$

For q = constant = q_o

$$\frac{d\rho c}{4 q_o} \left(T_w - T_i\right) = t \tag{9}$$

The temperature of the wire changes linearly with time.

However for a calorimeter gage, the heat transfer (q) is not necessarily constant, since the temperature difference between the wire and flow decreases as the wire heats up. Hot wire results [4] show that the Nusselt number is nearly constant for fixed flow conditions and all heat transfer rates.

Define $$Nu = \frac{Q}{\pi k l (T_r - T_w)} = \frac{q d}{k (T_r - T_w)}$$

Substituting into equation (7), we get

$$\frac{d \rho c}{4} \int_{T_i}^{T_w} \frac{dT_w}{\frac{Nu k}{d} (T_r - T_w)} = t = \frac{d^2 \rho c}{4 Nu k} \int_{T_i}^{T_w} \frac{dT_w}{T_r - T_w}$$

and $$T_w = T_r - (T_r - T_i) e^{-\frac{4 Nu k t}{d^2 \rho c}} \tag{10}$$

The time constant for this idealized case is the intercept of the initial slope of the response with T_r. This gives for the response time (a measure of the time for thermal adjustment of the wire)

$$\tau = \frac{d^2 \rho c}{4 Nu k} \tag{11}$$

Typical time constants range from .1 to 10 msec. Generally speaking these times are longer than the uniform flow times encountered in the shock tube.

The forced convection heat transfer rate to the wire is given by

$$Q = q \pi d l = \frac{\pi d^2 l}{4} \rho c \frac{dT_w}{dt}$$

Since

$$\Delta T = E / I R_i \alpha_i \quad \text{(constant current operation)}$$

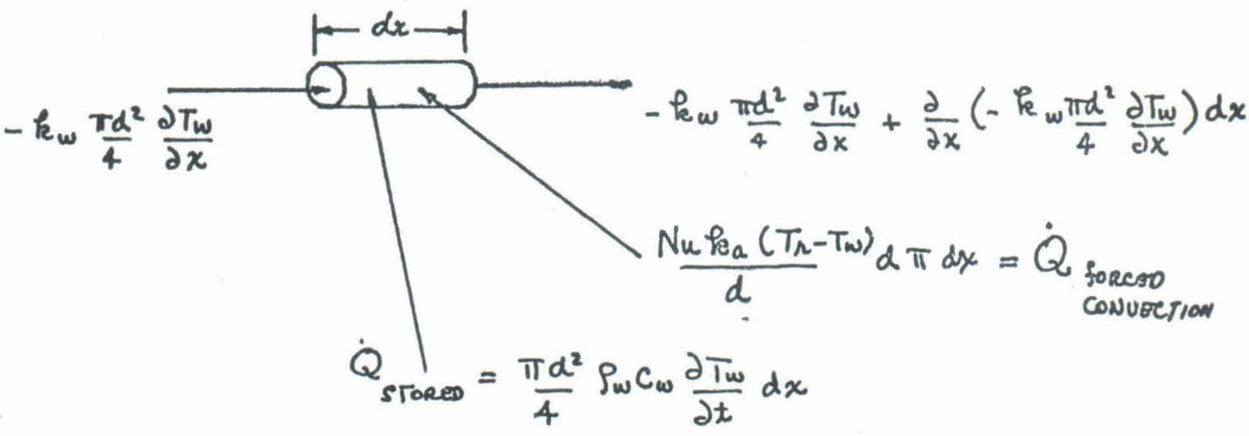
$$q = \frac{d\rho c}{4\alpha_i} \left(\frac{1}{IR_i} \right) \frac{dE}{dt} \tag{12}$$

Hence the heat transfer per unit area is directly proportional to the time rate of change of the voltage across the wire.

V. SUPPORT EFFECTS ON HEAT TRANSFER MEASUREMENTS

As has been mentioned previously, the wire and its supports begin to heat up after the passage of the shock wave. However, the supports do not heat up as rapidly as the wire does because of their large differences in mass. This causes a temperature difference to be set up between the wire and its supports. When this occurs the wire is no longer a perfect calorimeter because some heat is lost by conduction to the supports.

If heat transfer measurements are made at some time after the shock has passed by, some correction will have to be made to correct for this heat loss. It is the purpose of this section to estimate this correction. To make the mathematical problem more tractable the following assumptions are made 1) no radiation effects 2) no joule heating 3) the physical parameters are constant and 4) the Nusselt no. does not depend on the heat transfer rates. Consider the heat balance of a small differential element.



This results in the following differential equation:

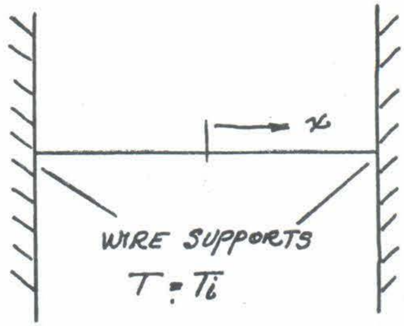
$$k_w \frac{d^2}{4} \frac{\partial^2 T_w}{\partial x^2} + Nu\, k_a (T_\lambda - T_w) = \frac{d^2}{4} \rho_w c_w \frac{\partial T_w}{\partial t} \tag{13}$$

Let

$$\nu = \frac{4 Nu\, k_a}{d^2 \rho_w c_w} \quad ; \quad \kappa = \frac{k_w}{\rho_w c_w} \quad ; \quad \Theta = \frac{T_w - T_i}{T_\lambda - T_i}$$

The boundary condition and the initial condition are assumed to be

$$\Theta(x,t) = \begin{cases} \Theta(x,0) = 0 \\ \Theta\left(\pm \frac{L}{2}, t\right) = 0 \end{cases}$$



$$\kappa \frac{\partial^2 \Theta}{\partial x^2} + \nu(1-\Theta) = \frac{\partial \Theta}{\partial t} \tag{14}$$

Apply the Laplace transformation to the time variable.

$$\frac{\partial^2 \tilde{\Theta}}{\partial x^2} - \left(\frac{\nu + s}{\kappa}\right)\tilde{\Theta} = -\frac{\nu}{s\kappa} \tag{15}$$

With the transformed B.C. the solution to this equation gives:

$$\tilde{\Theta}(x,s) = \frac{\nu}{s(\nu+s)}\left[1 - \frac{\cosh\sqrt{\frac{\nu+s}{\kappa}}\,x}{\cosh\sqrt{\frac{\nu+s}{\kappa}}\,\frac{L}{2}}\right] \tag{16}$$

This expression is then inverted with the help of reference 5.

$$\Theta = \frac{T_w - T_i}{T_t - T_i} = 1 - \frac{\cosh\sqrt{\lambda}\,\frac{2x}{L}}{\cosh\sqrt{\lambda}} - \frac{2}{\pi}\lambda e^{-t/\tau}\sum_{n=0}^{\infty}\frac{(-1)^n \cos\left[(n+\frac{1}{2})\frac{2\pi x}{L}\right] e^{-(n+\frac{1}{2})^2\pi^2\frac{t}{\tau\lambda}}}{(n+\frac{1}{2})\left[(n+\frac{1}{2})^2\pi^2 + \lambda\right]} \tag{17}$$

where $\lambda = \frac{Nu\, k_a}{k_w}\left(\frac{L}{d}\right)^2$ a non dimensional length

$\tau = \frac{d^2 \rho_w C_w}{4 Nu\, k_a}$ ideal two dimensional time constant of wire.

From this expression the average temperature ($\bar{T}_w$) can be calculated.

$$\frac{\overline{T_w}-T_i}{T_r-T_i} = \frac{2}{L}\int_0^{\frac{L}{2}} \frac{T_w-T_i}{T_r-T_i}\,dx = 1-\frac{1}{\sqrt{\lambda}}\tanh\sqrt{\lambda} - \frac{2}{\pi^2}\lambda e^{-t/\tau}\sum_{n=0}^{\infty}\frac{e^{-(n+\frac{1}{2})^2\pi^2\frac{t}{\tau\lambda}}}{(n+\frac{1}{2})^2\left[(n+\frac{1}{2})^2\pi^2+\lambda\right]} \tag{18}$$

This mean wire temperature represents the temperature that is used to calculate the voltage signal.

$$\dot{E} = I\dot{R}_w = IR_i\alpha_i\dot{\overline{T}}_w$$

The measured heat rate takes account only of the heat stored in the wire and this is equal to $\frac{\pi d^2 \ell}{4}\rho c\,\dot{\overline{T}}_w$ or:

$$\dot{Q}_{3D} = \frac{\pi d^2 \ell}{4}\rho c\,(T_r-T_i)\left[\frac{2}{\pi^2}\frac{e^{-\frac{t}{\tau}}}{\tau}\right]\left[\sum_{n=0}^{\infty}\frac{e^{-\frac{t}{\tau\lambda}(n+\frac{1}{2})^2\pi^2}}{(n+\frac{1}{2})^2}\right] \tag{19}$$

Ideally

$$\dot{Q}_{2D} = \frac{\pi d^2 \ell}{4}\rho c\,(T_r-T_i)\left[\frac{e^{-t/\tau}}{\tau}\right]$$

Therefore

$$\frac{\dot{Q}_{2D\ \text{IDEAL}\ \lambda\to\infty}}{\dot{Q}_{3D\ \text{MEASURED VALUE}}} = \frac{\pi^2}{2}\frac{1}{\sum_{n=0}^{\infty}\frac{e^{-(n+\frac{1}{2})^2\pi^2\frac{t}{\tau\lambda}}}{(n+\frac{1}{2})^2}} \tag{20a}$$

If $\frac{t}{\tau\lambda} \ll 1$, this function can be represented by

$$\frac{\dot{Q}_{2D}}{Q_{3D}} \cong 1 + \frac{2}{\lambda}\frac{t}{\tau} + \cdots \tag{20b}$$

At $t = 0$, the three dimensional heat transfer rate is identical with that of the two dimensional case and no end loss correction is needed. The time constant for the three dimensional wire is taken as the intercept of the initial slope of the wire's response with the equilibrium wire temperature.

Since the initial temperature slopes of the two and three dimensional wires are the same, the three dimensional time constant is related to the two dimensional one by

$$\tau_{3D} = \tau \left(\frac{\bar{T}_w - T_i}{T_r - T_i} \right)_{\substack{\text{equilibrium} \\ t \to \infty}} \tag{21}$$

A plot of the equilibrium wire temperature and $\frac{\tau_{3D}}{\tau}$ is given as function of λ in figure 2. Generally, λ is of the order 100, which gives a two per cent error in the measured heat transfer rate at $t/\tau = 1$.

VI. CALIBRATION OF THE GAGE

If the instrument is to be used for quantitative heat transfer measurements the physical and geometrical properties must be known. If only crude heat transfer measurements are to be made, handbook values of physical constants and manufacturer's specifications on the geometry would be acceptable. However, if more accurate results are desired individual calibration is necessary, since the above method is only good to $\pm$ 20%.

The separate quantity α can be determined by measuring the resistance of the wire between melting ice and boiling water. This is standard practice in hot wire anemometry. A sample from each spool of wire was calibrated in this fashion and the results were assumed to apply to the rest of the spool. This method is believed to give α to within one percent error. No attempt was made to calibrate the wire over a broader range of temperatures since it is believed that this calibration would be sufficiently accurate for wire temperatures up to 300°C, especially for tungsten. In almost all cases, the measured α was considerably lower than those quoted in the handbooks.

The diameter and length of the wire used in the gage can be determined optically. Since the diameter of the wire is very important in these heat transfer measurements, it is desirable to check the manufacturers quoted diameter. In most cases the wires diameters are within $\pm$ 5% of the quoted figure, although some wires exceed this considerably. A sample of each spool of wire was measured. The results were then assumed to apply to the whole spool.

The last constant to check is the combination ρc. An electrical means of calibration was chosen because it is fast, convenient, and accurate.

This type of calibration offers the additional convenience of easily checking the physical constants between shock tube runs. The method is to use a known heat input, measure the gage output and thereby determine the quantity ρc.

A constant current discharge was obtained by utilizing a capacitor with a time constant (RC) much longer than the testing time. The calibration circuit is shown in figure 3. This circuit is a slight modification of the bridge used by Josef Rabinowicz[6]. The calibration was done in air at atmospheric pressure. With the assumption of no end losses to the supports and no heat conduction to the surrounding fluid, the equation that governs the response becomes:

$$(d/dt)\, mc\, (T_w - T_i) = I^2 R_w \quad . \tag{22}$$

The assumption of no heat conduction to the surrounding medium is weak. The heat loss to the surrounding fluid is a strong function of time and diameter. In Section VII an attempt is made to evaluate this assumption. The heating current I is given by

$$I = \frac{V}{R_2 + R_w} \quad , \tag{23}$$

where R_w is the actual resistance of the gage at any time. Substituting into equation (22) gives

$$\frac{\pi d^2 \ell}{4} \rho c \frac{dT_w}{dt} = \frac{V^2}{(R_2 + R_w)^2} R_w = \frac{V^2 R_i \left[1 + \alpha_i (T_w - T_i)\right]}{(R_2 + R_i)^2 \left(1 + \frac{R_i \alpha_i (T_w - T_i)}{R_2 + R_i}\right)^2} \tag{24a}$$

If $\alpha \Delta T << 1$ (small times), the right side of the equation can be expanded

$$\frac{\pi d^2 \ell}{4} \rho c \frac{dT_w}{dt} = \frac{V^2 R_i}{(R_2+R_i)^2}\left[1 + \frac{R_2 - R_i}{R_2+R_i} \alpha_i \Delta T + \cdots \right] \tag{24b}$$

The solution of this equation with the initial condition $T_w = T_i$ at $t = 0$ gives for small times

$$T_w - T_i \cong \frac{4 V^2 R_i t}{\pi d^2 \ell \rho c (R_2+R_i)^2} + \cdots \tag{25a}$$

or

$$\Delta R = \frac{4 \alpha_i}{\pi d^2 \ell \rho c} \frac{V^2 R_i^2 t}{(R_2+R_i)^2} \tag{25b}$$

The voltage output ΔE of the bridge due to the heating of the wire is given by

$$\Delta E = \frac{V R_2 \Delta R}{(R_2+R_i)^2} \tag{26}$$

In this analysis both the changing current and resistance in the bridge was taken into account. This gives for ρc*

$$\rho c = \frac{V^3 R_2 R_i \alpha_i t}{\frac{\pi d^2 \ell}{4} (R_2+R_i)^4 E} \tag{27}$$

Figure (4) shows that for small testing times the response is indeed a straight line. Of course if the experimenter feels certain about the constant ρc, the calibration could be used to determine some other parameter (e.g. the diameter) or group of parameters.

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* Caution should be used with the electrical discharge technique. The energy produced and stored in the wire must not raise the temperature of the wire more than a few hundred degrees. The voltage used for calibration must be varied accordingly.

If care is taken to measure the resistances, voltages, and volumes to 1/2% accuracy, the overall calibration should be better than 5%. The calibrations of each gage were repeatable to 1%. The values of ρc for tungsten wire used in this report varied between .6 and .65 $\frac{\text{cal}}{\text{cm}^3\,{}^\circ\text{C}}$. The handbook value is approximately .62 $\frac{\text{cal}}{\text{cm}^3\,{}^\circ\text{C}}$. It is felt that most of this variation of ρc actually represents the variance of the other physical and geometrical properties of the wire since these were determined by spool values rather than individual calibrations.

VII. ESTIMATE OF HEAT CONDUCTION LOSSES TO THE SURROUNDING MEDIA DURING CALIBRATION

In calibrating the wire, some error is introduced due to the heat conduction to the surrounding medium. Figure (5) shows this effect. The rate at which heat is lost will be a function of the diffusivity of the surrounding medium, time, diameter of the wire, and other physical constants which are usually kept constant during all the calibrations. The ratio of heat conduction rate to the stored heat rate is the error in the calibration due to the presence of this heat loss mechanism.

$$\frac{\dot{Q}_c}{\dot{Q}_s} = \varepsilon \tag{28}$$

It is this function that is studied here.

The value of $\dot{Q}_c$ requires the complete solution of the heat equation in cylindrical coordinates with the appropriate initial conditions.

$$\frac{k_a}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = \rho_a c_a \frac{\partial T}{\partial t}$$

No solution of this equation in closed form could be found even for the simple case of a step rise in temperature of the wire [7].

Dimensional Analysis suggests that the heat lost by conduction is represented by

$$q_c = \frac{k_a(T_w - T_a)}{d}\, f\left(\frac{d^2 \rho_a c_a}{4 k_a t}\right) \tag{29a}$$

or

$$\dot{Q}_c = k_a(T_w - T_a)\,\pi \frac{\ell d}{d}\, f\left(\frac{d^2 \rho_a c_a}{4 k_a t}\right) \tag{29b}$$

The stored heat rate is

$$\dot{Q}_s = \frac{d}{dt}\left[\frac{\pi d^2 \ell}{4} \rho_w c_w (T_w - T_i)\right] = \frac{\pi d^2 \ell}{4} \rho_w c_w \dot{T}_w \tag{30}$$

Therefore

$$\frac{\dot{Q}_c}{\dot{Q}_s} = \frac{4 k_a (T_w - T_a)}{d^2 \rho_w c_w \dot{T}_w} f\left(\frac{d^2 \rho_a c_a}{4 k_a t}\right) = \varepsilon \tag{31}$$

In the case of calibration of the wire, $(T_w - T_a)$ is approximately represented by the function At, where A is a constant.

$$\frac{\dot{Q}_c}{\dot{Q}_s} = \frac{4 k_a A t}{d^2 \rho_w c_w A} f\left(\frac{d^2 \rho_a c_a}{4 k_a t}\right) = \frac{4 k_a t}{d^2 \rho_w c_w} f\left(\frac{d^2 \rho_a c_a}{4 k_a t}\right) \tag{31}$$

The empirical form of f is approximated by

$$f = B\left(\frac{d^2 \rho_a c_a}{4 k_a t}\right)^{\beta} \tag{32}$$

Fitting this to the calibration experiments gives

$$B = 1 \pm 20\% ; \qquad \beta = .07 \pm 10\%$$

in the range

$$1 < \frac{d^2 \rho_a c_a}{4 k_a t} < 100$$

Substituting equation (32) into equation (31) gives

$$\varepsilon = \left(\frac{4 k_a t}{\rho_w c_w d^2}\right)\left(\frac{d^2 \rho_a c_a}{4 k_a t}\right)^{.07} \tag{33a}$$

The density of the surrounding medium can be written in terms of pressure and temperature with the help of the ideal gas law.

$$\varepsilon = \left(\frac{4 k_a t}{\rho_w c_w d^2}\right)\left(\frac{d^2 p_a c_a}{4 k_a R_a T_a t}\right)^{.07} \tag{33b}$$

This formula shows the strong dependence of the calibration error on the diameter of the wire and time while the pressure has only a slight effect. If the allowable error is one percent, the maximum permissible calibration time is approximately 200 μsec for a 1 mil wire and only 2 μsec for a 1/10 mil wire, under atmospheric conditions. For accurate calibration, the calibration time must be reduced drastically with diameter.

VIII. OPERATING TECHNIQUE

In making heat transfer measurements with this instrument, the wire's initial resistance is measured on a wheatstone bridge. The bridge also supplies the necessary excitation current which is monitored by a 1 ohm precision resistor and a Leeds and Northrup potentiometer. This current is kept constant by a swamping resistor in the bridge circuit which is 100 to 1000 times larger than the gage resistance. Gage resistances and excitation currents vary with the diameter. Typical values are:

R 2-40 ohms

I 20-1 ma

The signal is recorded on a Textronix 535 oscilloscope which is triggered by the passing of the shock wave. With careful calibration of the oscilloscope and gage, heat transfer measurements can be made to 5%. The gage calibration does not appreciably change if the initial resistance of the wire remains constant*. A variance in the initial resistance of the wire of one percent may indicate that recalibration is needed to correct for a small change in this gage constant. The tungsten wires have an amazing durability if carefully built. Wires made from .0005" W have lasted more than 20 consecutive runs in the shock tube at $M_S \sim 4$, and $p_1 \sim 10$ mm Hg.

Figure 6 illustrates the circuit used for heat transfer measurements.

---

* As a rule some surface deterioration of the wires would be expected due to oxidation at the elevated wire temperatures in the hot flow. No large deterioration has been noticed due to this mechanism even after many consecutive runs in the shock tube. This is attributible to the short testing times involved. If the wire is in a reasonably stable state (i.e. not undergoing a phase transition), this fact permits the wire to be used consecutively without recalibration or at least with a minimum of recalibration.

IX. PRELIMINARY HEAT TRANSFER MEASUREMENTS

Preliminary heat transfer measurements were made on some fine wires. After the passage of the initial shock wave the wires response should follow equation (10). If the flow times are short compared to τ, the heat transfer is nearly constant and the response is a straight line. If the flow time is long compared to the time constant, the response is exponential. Figure (7) depicts these two conditions.

In this figure the termination of the hot flow is denoted by the first discontinuity after the arrival of the shock. This discontinuity is the contact surface and has been used in the study of the duration of the hot flow in the shock tube[8].

The results of several runs are shown in figure (8). For the pressures and Mach nos. shown the heat transfer is proportional to $\sqrt{\frac{p}{d}}$ as one would expect from hot wire data.

X. CONCLUDING REMARKS

This report has described the application of fine cold wires for heat transfer measurements in the shock tube. With proper care taken in constructing and calibrating the wire, quantitative heat transfer measurements can be taken. The electrical calibration in air described herein has proved satisfactory, provided that any heat conduction to the surrounding media has been taken into account. Under conditions of radically changing heat transfer rates, the wires can be used as shock detection devices, contact surface detectors, or other timing operations.

It is convenient now to summarize some of the features of a fine cold wire as used in the shock tube.

1) Because the wire is not preheated, it maintains the temperature of its supports. Therefore, after the shock wave has passed over the wire, initially there are no end loss corrections.
2) No oxidation or surface deterioration of the wire due to preheating the wire.
3) Since end loss corrections are initially zero, a smaller aspect ratio (ℓ/d) can be used resulting in less wire breakage.
4) Heat transfer signals are easily interpreted and have no memory*.
5) The response time is of order $\frac{d}{U}$. For moderate shock speeds, this time is less than 1 μsec.

With its fast response time the gage should be applicable to many short duration flow problems with a hot gas.

---

* The well known one dimensional heat transfer gage is an example of an instrument that has a memory. The heat transfer is related to the surface temperature by $q = A \int_0^t \frac{T'(\tau)\, d\tau}{\sqrt{t-\tau}}$. The integrand contains a weighting term that weights past times.

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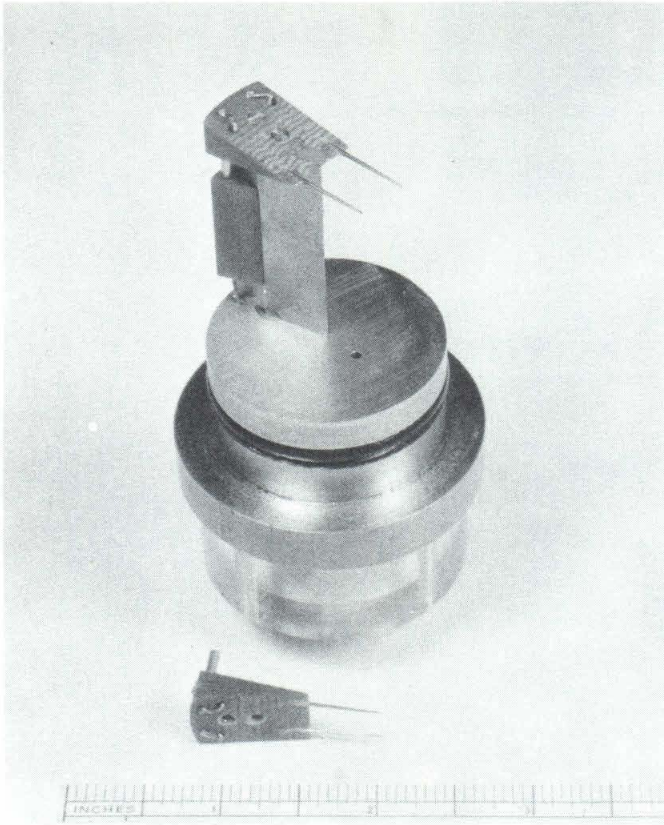


FIGURE 1

THE GAGE AND ITS MOUNTING

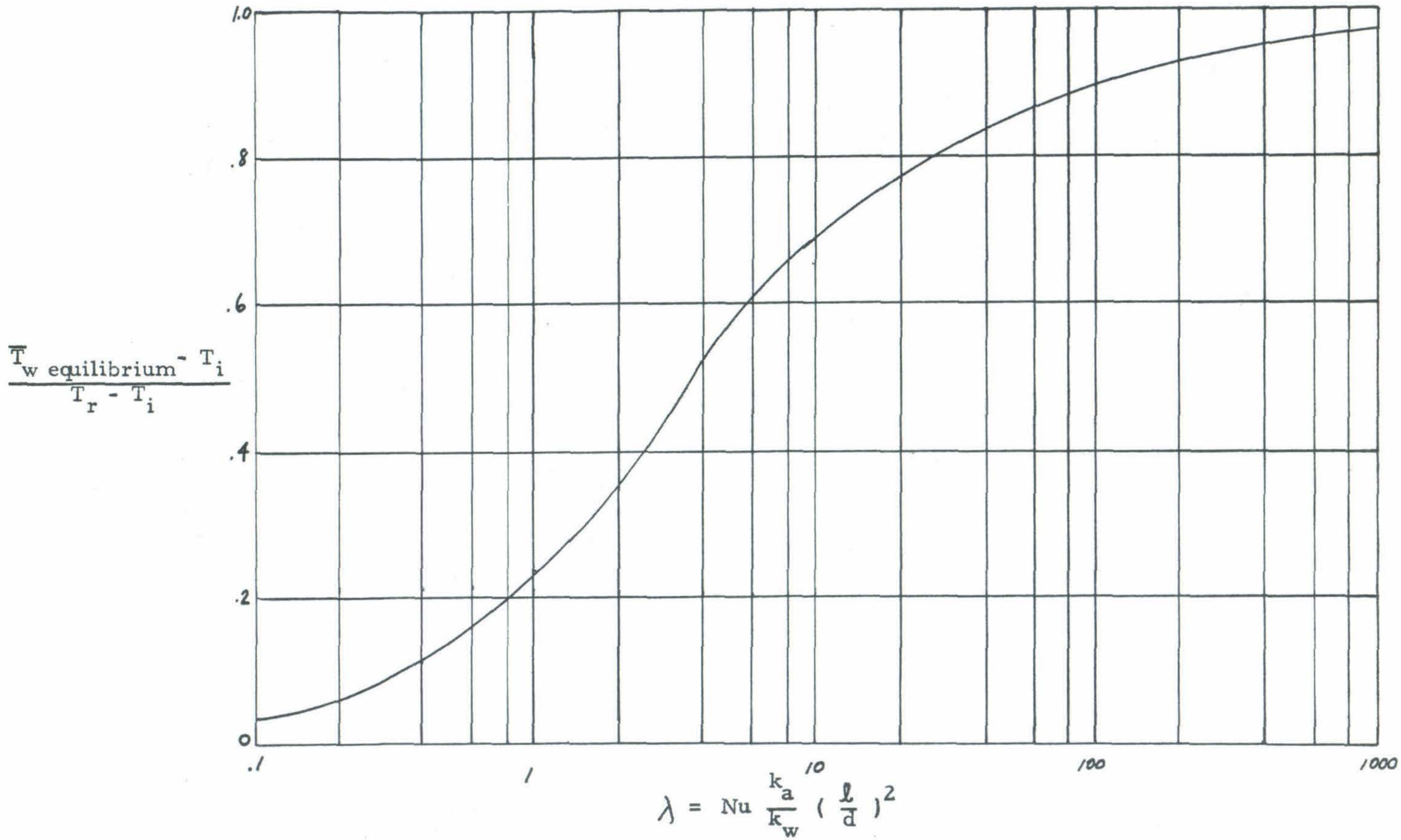
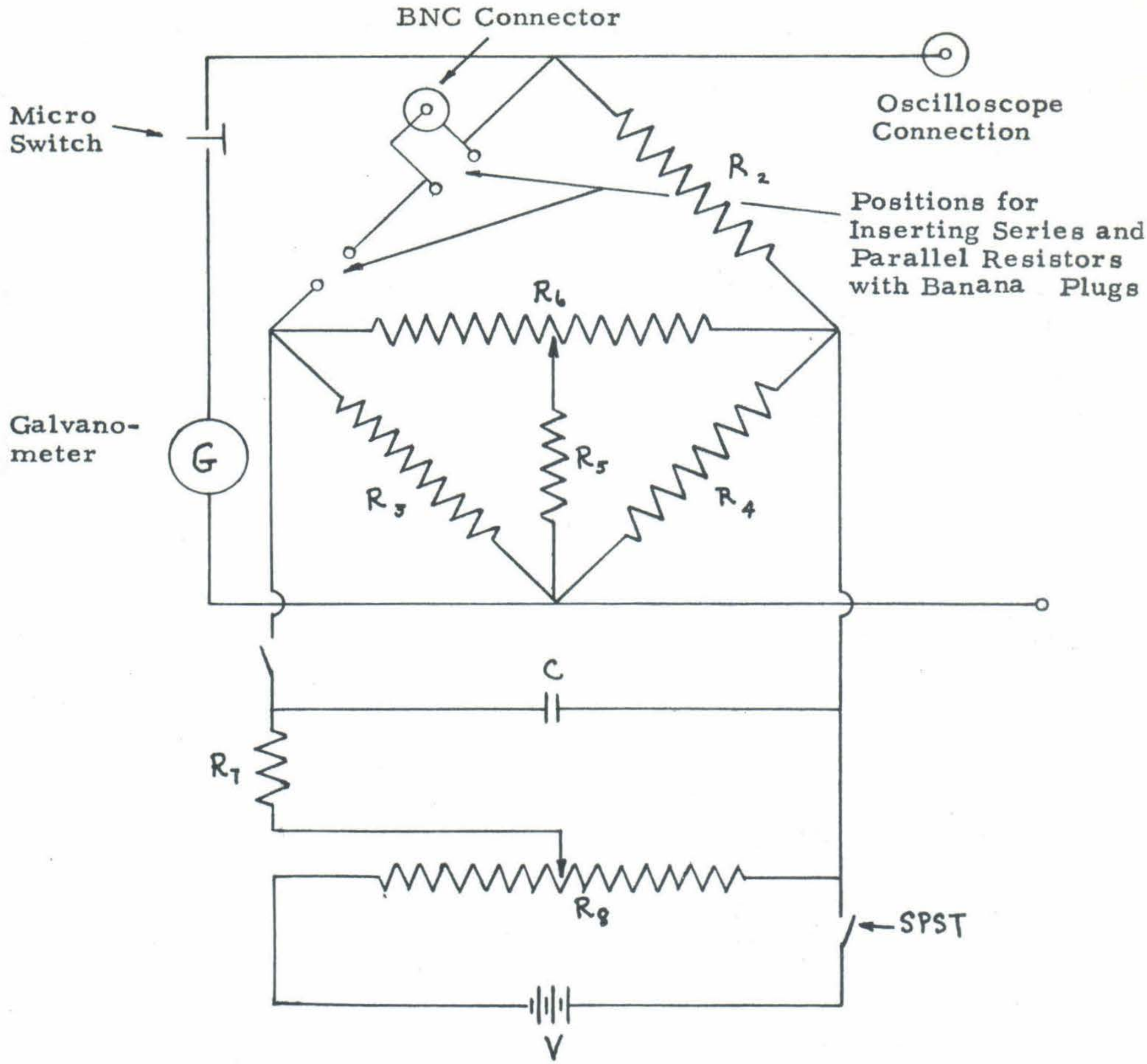


FIGURE 2

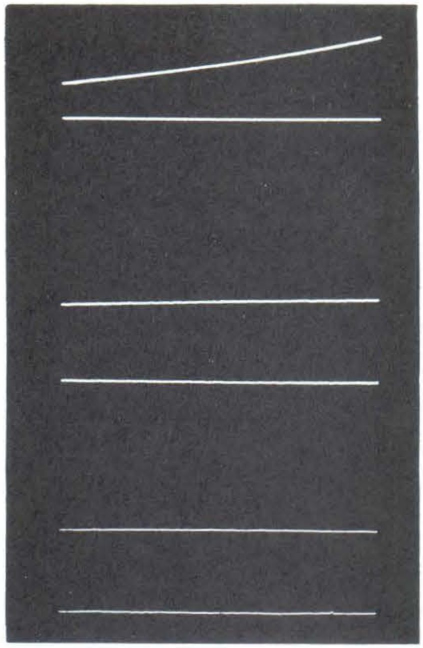
EQUILIBRIUM TEMPERATURE OF THE WIRE AS A FUNCTION OF THE WIRE GEOMETRY



$R_w = R_3 = R_4 = 50$ ohm
$R_5 = 500$ ohm
$R_6 = 0 - 1000$ ohm
$R_7 = 1000$ ohm
$R_8 = 0 - 1000$ ohm (.25% linearity Helipot)
C = 250 microfarads

FIGURE 3

CALIBRATION CIRCUIT

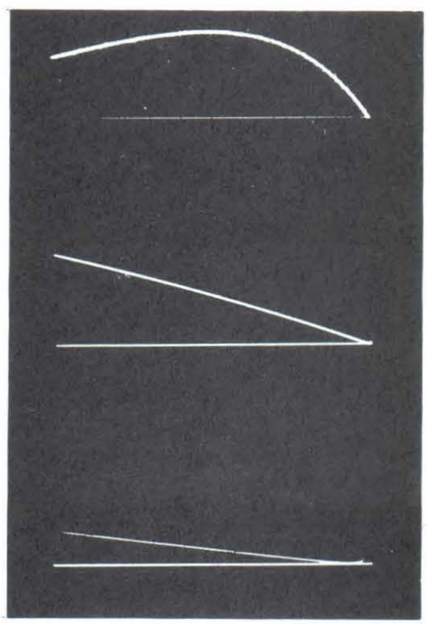


1,000 μsec/cm

100 μ sec/cm

10 μsec/cm

(a) Stable Resistance



1,000 μsec/cm

100 μ sec/cm

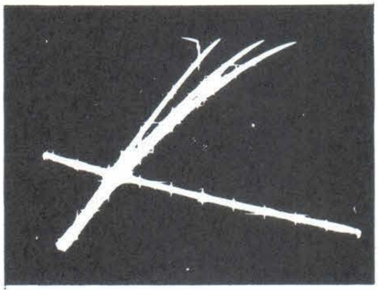
10 μ sec/cm

(b) Wire Resistance

FIGURE 4

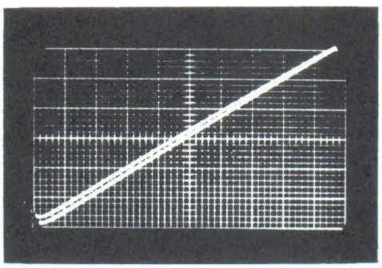
CHARACTERISTICS OF CALIBRATION CIRCUIT

400 μ Hg
100 mm Hg
750 mm Ha



Wire Material:	Platinum
Diameter:	.0005"
Sweep:	500 μsec/cm
Calibration:	50 mv/cm

750 mm Hg



1.5 mm Hg

Wire Material:	Tungsten
Diameter:	.001"
Sweep:	100 μsec/cm
Calibration:	10 mv/cm

FIGURE 5

EFFECT OF SURROUNDING MEDIA ON
GAGE OUTPUT DURING CALIBRATION

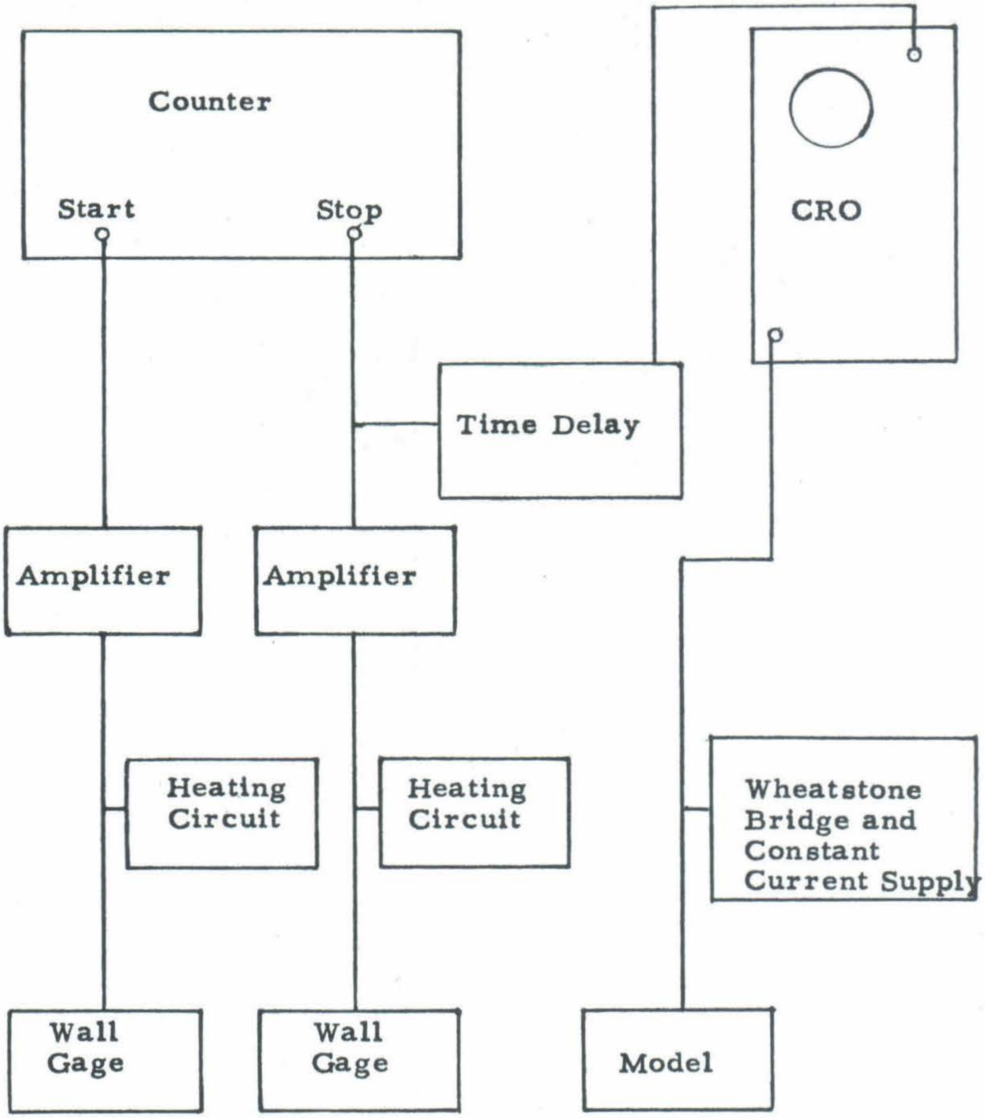
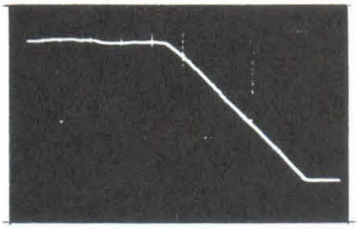


FIGURE 6

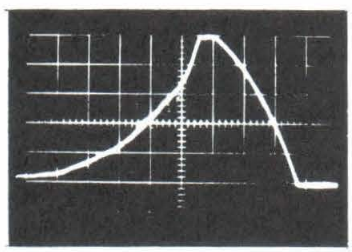
BLOCK DIAGRAM OF GAGE AND SHOCK TUBE FOR HEAT TRANSFER MEASUREMENTS



$t/\tau << 1$

Sweep: 100 μsec/cm
Material: Tungsten
d: =.001"

Experimental Flow Duration: 450 μsec
τ = 3400 μ sec
t/τ = .132



$t/\tau \cong 1$

Sweep: 200 μ sec/cm
Material: Tungsten
d: = .0002"

Experimental Flow Duration: 540 μsec
τ = 485 μ sec
t/τ = 1.11

FIGURE 7

TYPICAL GAGE RESPONSES IN THE SHOCK TUBE

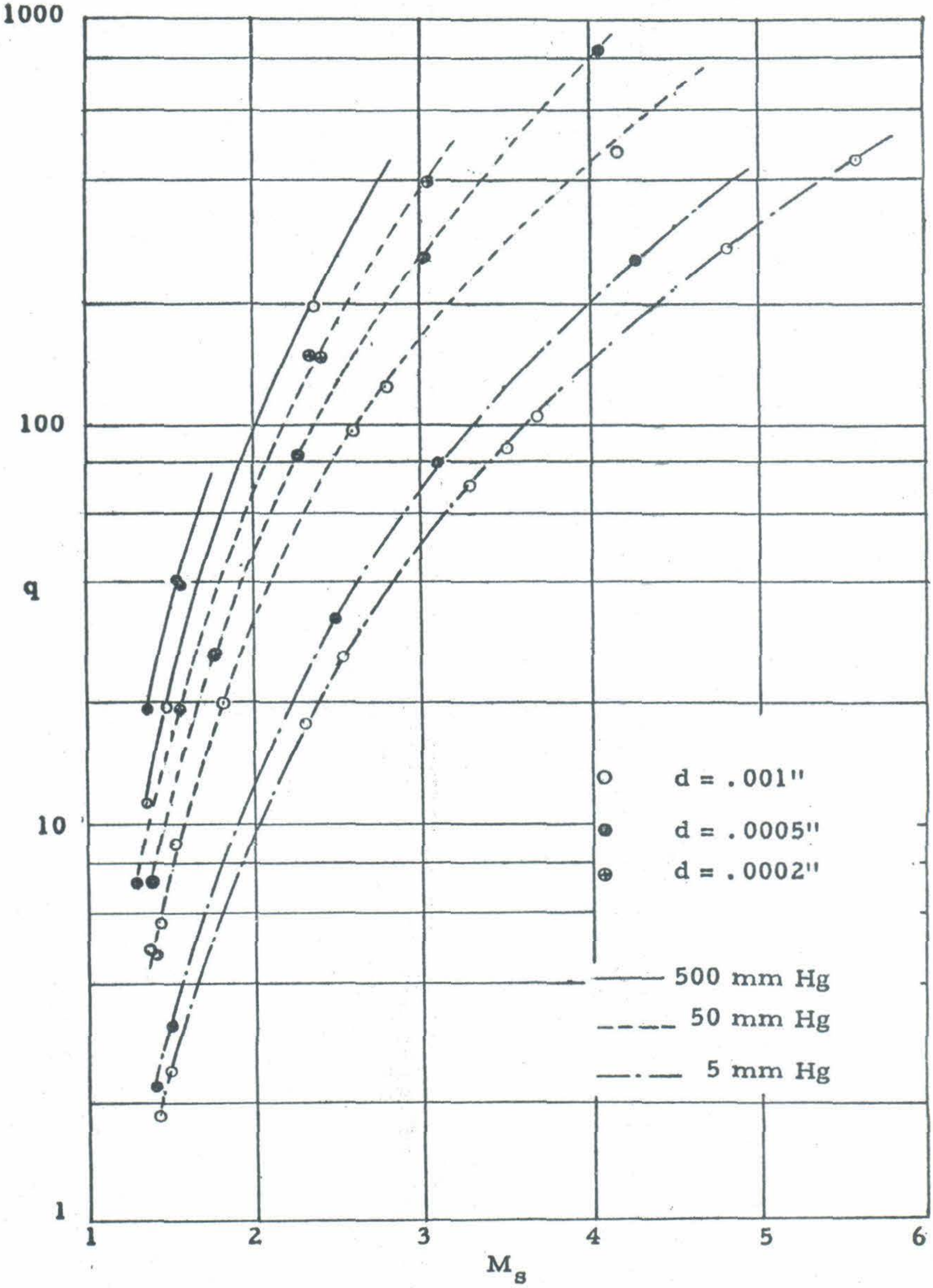


FIGURE 8a

PRELIMINARY RESULTS

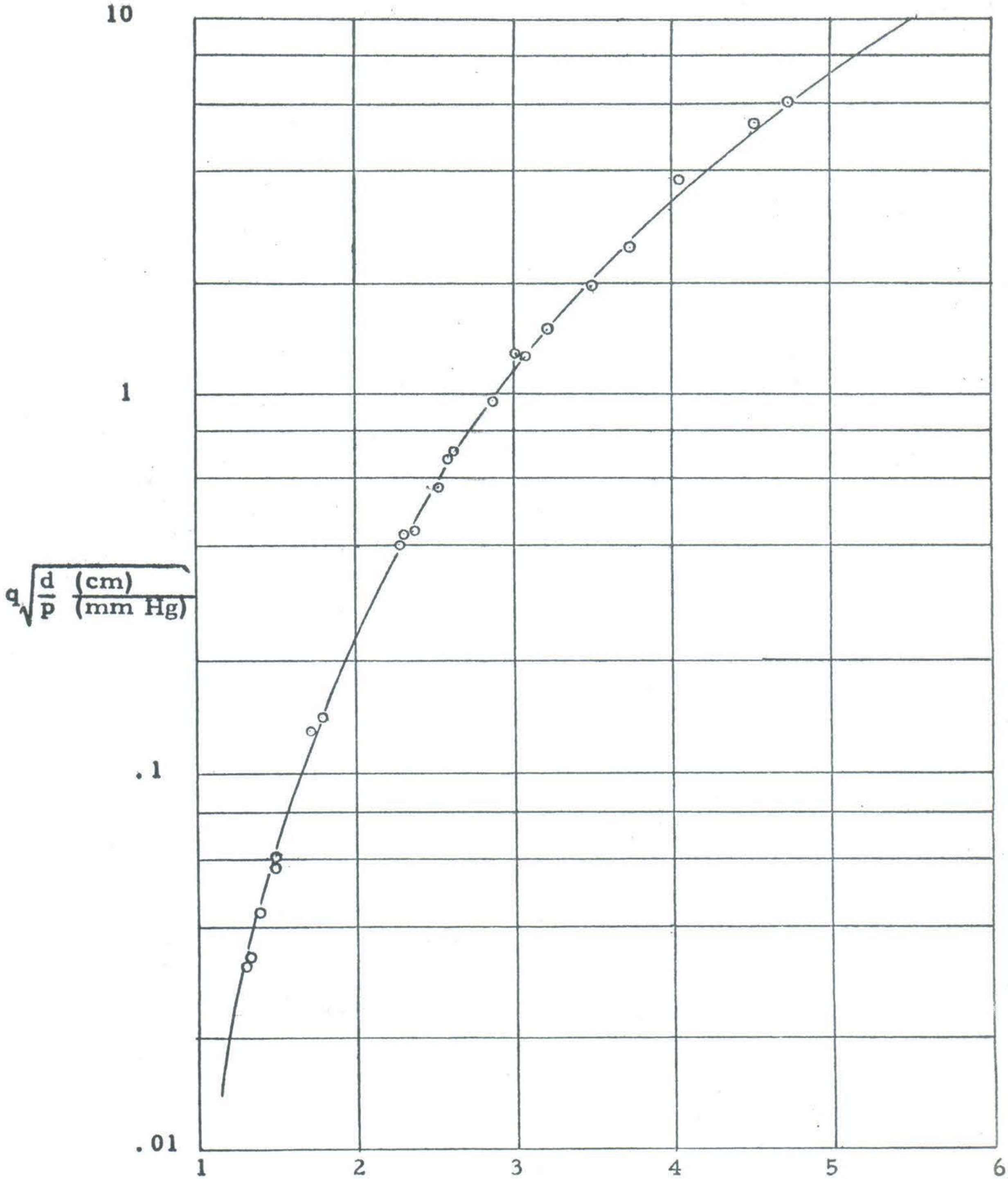


FIGURE 8b

PRELIMINARY RESULTS

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